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Effects of Sulfuric Acid Rain on Decomposition Rate and Chemical Element Content of Hardwood Leaf Litter

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16. ABSTRACT

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Effects of sulfuric acid rain on decomposition rate and chemical element content of hardwood leaf litter

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Des paquets de feuilles en décomposition de 10 espèces de bois francs ont été soumis à une pluie simulée d'acide sulfurique (pH de 3,0, 3,5 ou 4,0) ou à une pluie témoin (pH de 5,6). Les changements dans le poids et dans la concentration des éléments chimiques ont été suivis pendant 408 jours. Le poids des paquets de feuilles diminue le plus rapidement dans les traitements d'acidité intermédiaire, surtout à pH 3,5. Le rapport du taux de décomposition des feuilles à pH 3,5 sur le taux de décomposition des feuilles témoins varie de 1,10 pour *Quercus garryana* à 12,57 pour *Quercus palustris*. Tel que prévu, les taux de décomposition des feuilles témoins ont tendance à être plus élevés chez les espèces ayant un rapport C:N faible et une teneur élevée en bases. Cependant, il n'y a aucune relation évidente entre l'effet de la pluie d'acide sulfurique sur le taux de décomposition et le contenu initial en éléments chimiques. L'absence de relation entre cet effet et la concentration de S ou le rapport S:N suggère que la pluie d'acide sulfurique n'augmente par la décomposition par l'apport de soufre; cependant, le S provenant de la pluie est sûrement plus disponible que le S d'origine organique. Dans tous les traitements sauf à pH 3,0, la concentration de Mn augmente d'abord, puis elle diminue. Après 408 jours, la concentration de Mn est beaucoup plus faible à pH 3,0 qu'à tous les autres traitements. Le manganèse est le seul élément dont la concentration dépende du traitement à l'acide sulfurique.

[Traduit par le journal]

Introduction

Precipitation containing significant amounts of nitric acid and sulfuric acid falls over large portions of North America. In the eastern region, annual average pH values range down to 4.0; seasonal averages can be even lower. By comparison, unpolluted rain containing only carbonic acid in equilibrium with atmospheric CO_2 would have an average pH of 5.6 (Likens *et al.* 1979). The strong mineral acids now found in precipitation are derived primarily from the long-range transport and conversion of the air pollutants sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) (Likens *et al.* 1979).

Areas receiving acid precipitation encompass vast tracts of forest. Compared with highly managed agricultural land, forests receive little, if any, planned inputs of nutrients. In forest systems, biological and chemical cycling regulate the availability of essential nutrients. While changes in the annual rates at which nutrients are returned to the soil could directly alter nutrient pools, shifts in timing of the release of nutrients within the annual cycles could alter availability of specific nutrients during peak growth periods. In turn, these shifts could alter the productivity of individual species (especially species with short growing seasons, such as ephemerals), community structure, and the rate of loss of nutrients through leaching. Thus, the potential alteration of litter decomposition and nutrient cycling by acid precipitation has been identified as an area of concern (Galloway *et al.* 1978; Hutchinson and Havas 1980; Anonymous 1976; Anonymous 1979), especially

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for forests in eastern North America (Altshuller and McBean 1980).

The greatest concern expressed by the authors cited above has been for potential decreases in decomposition rates. However, previous experimental studies of the effects of acid precipitation on the decomposition of coniferous leaf litter have shown that both higher and lower decomposition rates, as measured by weight loss, can be associated with more acidic conditions. Abrahamsen *et al.* (1980) reported results from three laboratory studies. The decomposition rates of green needles of Norway spruce (*Picea abies* (L.) Karst.; unless otherwise indicated, nomenclature follows Hosie 1969) were not affected by simulated acid rain treatments of pH 2 and 3. However, when lodgepole pine (*Pinus contorta* Dougl.) needles from different sites were allowed to decompose under identical conditions, needles from sites which had received supplemental sulfuric acid rain decomposed 30% faster than those from sites which had received only supplemental control rain. However, Abrahamsen *et al.* (1980) also found that raw pine humus decayed 11% more slowly under simulated acid rain than under simulated control rain.

The effects of acid precipitation on decomposition rates of coniferous leaf litter also have been evaluated under field conditions using the litter bag method. Baath *et al.* (1980) reported decreases of 5–10% in decomposition rates of Scots pine (*Pinus sylvestris* L.) needles on sites which had been acidified by adding sulfuric acid. However, Roberts *et al.* (1980) found that pine needles decayed 15% faster on acid-treated sites.

All of the above studies involved coniferous species, which produce relatively acidic litter. Thus, it is possible that the organisms involved were acid adapted and less susceptible to inhibition by acid rain than would be true for organisms in deciduous litter.

In this paper we report the results of our studies on the effects of simulated sulfuric acid rain on the decomposition (weight loss and changes in elemental concentration) of leaf litter from 10 hardwood tree species. The leaves were obtained from trees growing in an area not subject to acid rain. (National Atmospheric Deposition Program (NADP) data from this location indicate an average rain pH of 5.6, with occasional events down to pH 5.0.) Thus, differences in decomposition rates within species were directly caused by simulated sulfuric acid rain and not by initial differences in substrate or in decomposer populations associated with previous exposure to strongly acidic ambient rain.

Materials and methods

A soil mixture containing equal parts of Bohannon topsoil (Anonymous 1973), silica sand, and pea gravel was placed in cedar flats (37 × 51 × 8.5 cm) to a depth of 6 cm. The Bohannon topsoil, from the Siuslaw National Forest, Oregon, had previously sustained a Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) and red alder (*Alnus rubra* Bong.) community. It is a moderately well-drained clay loam with a pH of 5.4, a base saturation of 11%, a cation exchange capacity of 32 mequiv./100 g, and a strong sulfate-absorbing ability (Lee and Weber 1982; Johnson and Cole 1977). Flats were lined with polyethylene; openings were made for drainage. A thin layer of organic matter, taken from the O2 soil horizon of a bigleaf maple (*Acer macrophyllum* Pursh) or Garry oak (*Quercus garryana* Dougl.) stand, was placed on the soil surface.

Fallen leaves of 10 hardwood tree species were collected in November 1976, within a 20-km radius of the Environmental Protection Agency's Corvallis Environmental Research Laboratory in Corvallis, Oregon, air dried, and stored in an unheated building. Leaf packs were formed by sewing together five leaves (or leaflets for Oregon ash) of a given species with nylon thread. A plastic label was also sewn to each pack. The packs were then dried at 25°C, weighed, placed in the flats (nine packs per species per flat), and covered with approximately 1 to 2 cm of loose leaf litter. Each flat was covered with nylon netting (approximately 3-cm mesh).

Five flats were placed at each of eight stations under a transparent vinyl roof (nominally, 90% transmittance of light) with open ends and sides. Stations were located 3 m apart along a line oriented east to west. Flats were thus exposed to near-ambient environmental conditions, except for precipitation. The facility was located on the Schmidt Research Farm of Oregon State University, near Corvallis, Oregon.

One flat at each station contained leaf packs of Garry oak (average weight, 1.94 g/pack) and pin oak (*Quercus palustris* Muench., 1.06 g/pack), covered with loose Garry oak litter. This flat also contained (on the soil surface) organic matter from the O2 soil horizon of a Garry oak stand; all other flats had O2 material from a bigleaf maple stand. The second flat contained leaf packs (without petioles) of bigleaf maple (4.47 g/pack) and Oregon ash (*Fraxinus latifolia* Benth., 1.17 g/pack) covered with a mixture of maple and ash litter. Leaf packs of tulip-tree (*Liriodendron tulipifera* L., 2.09 g/pack) and sweetgum (*Liquidambar styraciflua* L., 2.09 g/pack; without petioles) were placed in the third flat and covered with mixed litter of these two species. Nomenclature for *L. styraciflua* follows Bailey and Bailey (1976). The fourth flat contained black cottonwood (*Populus trichocarpa* Torr. and Gray, 3.24 g/pack), scouler willow (*Salix scouleriana* Barratt, 1.13 g/pack), and white elm (*Ulmus americana* L., 1.78 g/pack) leaf packs with a cottonwood litter layer. Sycamore (London plane-tree, *Platanus acerifolia* (Ait.) Willd., 6.27 g/pack) leaf packs and litter were placed in the fifth flat. Petioles were removed from leaves of *Acer macrophyllum* and *Liquidambar styraciflua* because of the limited space available in the flats.

At two stations, the flats received a simulated control rain (pH 5.6) containing 11 μequiv./L Ca^{2+}, 12 μequiv./L NH_4^+, 5 μequiv./L Na^+, 2 μequiv./L K^+, 5 μequiv./L Mg^{2+}, 11 μequiv./L SO_4^{2-}, 12 μequiv./L NO_3^-, and 12 μequiv./L Cl^-. At three pairs of stations, sufficient H_2SO_4 was added to the control rain to lower the pH to 4.0, 3.5, or 3.0. Rain was applied at the rate of 2.5 mm/h for 3 h per day, 3 days per week.

The flats were prepared in December 1976. At the same

TABLE 1. Decomposition constants, k, of hardwood leaves subjected to simulated sulfuric acid rain (k values in years^{-1})

Species	pH of treatment				Significance level*
	3.0	3.5	4.0	Control	
Acer macrophyllum	0.88	2.32	0.50	1.50	0.001
Populus trichocarpa	0.80	1.37	0.68	1.09	0.415
Quercus garryana	0.84	1.16	1.10	1.05	0.251
Fraxinus latifolia	1.57	1.85	1.51	0.89	0.045
Ulmus americana	1.12	1.41	0.62	0.54	<0.001
Liriodendron tulipifera	0.74	1.83	1.04	0.48	0.005
Salix scouleriana	0.42	0.56	0.40	0.27	0.002
Liquidambar styraciflua	0.19	0.32	0.25	0.24	0.166
Platanus acerifolia	0.24	0.23	0.19	0.15	0.189
Quercus palustris	−0.04	0.38	0.75	0.03	0.019

*Probability of type I error, based on F test for treatment effect.

time, a sample of leaves of each species was dried and ground for chemical analysis. Three leaf packs of each species were removed from each station (two stations per treatment) after 90, 300, and 408 days. The leaf packs were dried at 25°C, weighed, and ground for chemical analysis. Organic carbon, Kjeldahl nitrogen, phosphorus, calcium, magnesium, sulfur, iron, manganese, strontium, and potassium were determined for each species from composite samples from each flat, as well as for the initial sample of each species. In some cases of advanced decomposition, insufficient tissue was available for chemical analysis.

Samples were prepared for metal and sulfur analysis by digestion with HNO_3 and $HClO_4$, following a procedure similar to that of McQuaker *et al.* (1979). Every 8th sample was run in duplicate, and every 10th sample consisted of standard orchard leaves obtained from the United States National Bureau of Standards (NBS 1571). Metals (except potassium) were determined by an inductively coupled plasma atomic emission spectrometer. Potassium analysis was by atomic absorption spectrometer in flame emission mode; sulfur was determined turbidimetrically (Hunt 1980; Fernandez *et al.* 1980).

Kjeldahl nitrogen and phosphate phosphorus analyses were performed on separate aliquots obtained by digesting samples with a catalyst sulfuric acid mixture. After digestion the samples were diluted and analyzed on the Technicon automated system (Jirka *et al.* 1976). Every fifth sample was run in duplicate. Standard samples of spinach (NBS SRM 1570), orchard leaves (NBS 1571), tomato leaves (NBS 1573), and pine needles (NBS 1575) were routinely analyzed for Kjeldahl nitrogen and phosphate phosphorus.

Chloride was analyzed according to the procedure of Adriano *et al.* (1973). The CHN automated method (Horowitz 1975) was used for carbon. Replicates were run and comparisons were made between nitrogen values from CHN analysis and nitrogen from Kjeldahl nitrogen analysis. Samples used for CHN analysis were substantially smaller than those used for Kjeldahl nitrogen analysis (1 mg compared with 50 mg), resulting in much larger uncertainties in nitrogen concentrations. However, within this limitation, the results from the two procedures compared favorably.

Decomposition constants, k, were determined by fitting the regression equation $\ln(W/W_0) = -kt$, where W was the weight of a leaf pack at time t, and W_0 was the weight at $t = 0$ (Olson 1963). F tests were used to determine if k was dependent on sulfuric acid rain treatment.

Analysis of variance was performed on the logarithms of chemical concentration. F tests were used to test for variation over time and for treatment effects.

Results

Decomposition constants, k, for each species and treatment are given in Table 1. Significant effects of acidity on decomposition ($p < 0.05$) were found for 6 of the 10 species. The remaining four species showed similar trends, but at nonsignificant levels.

For all species except *Platanus acerifolia* maximum decomposition constants occurred at pH 3.5 (eight species) or 4.0 (one species). The k value for *Platanus acerifolia* was greatest at pH values of 3.0 and 3.5. Addition of simulated sulfuric acid rain accelerated litter decomposition, although not equally at all pH levels. The k value was greater than control for all 10 species at pH 3.5, for 8 species at pH 4.0, and for 5 species at pH 3.0.

The largest response to sulfuric acid rain was for *Quercus palustris*; acid-treated leaves of this species decayed up to 25 times faster than leaves in the control. Decomposition of *Fraxinus latifolia*, *Liriodendron tulipifera*, *Salix scouleriana*, and *Ulmus americana* leaves under acid rain treatment was two to three times faster than that of control leaves.

Table 2 summarizes the control decomposition constants, k_c, and the initial values of various chemical concentrations and ratios. The ratio of the decomposition constant at pH 3.5, $k_{3.5}$, to k_c is also given; for most species, this ratio represents the greatest effect of simulated sulfuric acid rain on the decomposition rate. The species are listed in decreasing order of k_c.

TABLE 2. Summary of decomposition constants and initial chemical concentrations in leaves. Species are listed in decreasing order of control decomposition constant, k_c

Species	k_c, year^{-1}	$k_{3.5}$: k_c	C:N	S:N	C:S	S*	P*	K*	Fe*	Mn*;	Sr*	Mg + Ca, equiv./100 g
Acer macrophyllum	1.50	1.55	45.5	0.123	330	1350	1200	3700	438	690	134	0.15
Populus trichocarpa	1.04	1.26	53.2	0.143	357	1100	650	2200	488	62	255	0.24
Quercus garryana	1.05	1.10	37.5	0.075	501	900	790	2300	492	350	97	0.11
Fraxinus latifolia	0.89	2.08	44.7	0.117	361	1100	1200	2100	730	51	165	0.18
Ulmus americana	0.54	2.61	51.3	0.181	571	600	860	1600	464	58	104	0.17
Liriodendron tulipifera	0.48	3.81	69.9	0.163	447	1000	350	2800	236	720	173	0.14
Salix scouleriana	0.27	2.07	66.7	0.079	319	1300	810	3100	194	461	75	0.11
Liquidambar styraciflua	0.24	1.33	—	—	647	600	540	3100	152	1200	63	0.08
Platanus acerifolia	0.15	1.53	74.3	0.354	224	2000	570	2800	458	110	159	0.14
Quercus palustris	0.03	12.67	82.7	0.900	771	600	270	3300	194	445	33	0.04

*Parts per million (weight).

Increased decomposition rates under sulfuric acid rain, represented by $k_{3.5}$:k_c in Table 2, did not depend in an obvious way on any of the measured chemicals. For example, *Acer macrophyllum* and *Platanus acerifolia* had similar values of $k_{3.5}$:k_c; however, these species had quite different values of k_c, C:N, S, S:N, P, K, and Mn. While initial values of bases (Mg + Ca), Fe, and Sr were similar for these two species, no relationship between $k_{3.5}$:k_c and these chemicals is evident among the other species.

Changes in elemental concentrations are summarized in Table 3. Entries in this table are expressed as ratios of final values (400 days) to initial values. N, S, P, and Fe concentrations tended to increase for most species, while K and Mg concentrations tended to decrease. Changes in Ca and Sr were highly dependent on species, with increases and decreases having occurred with approximately equal frequency.

Although statistically significant variation over time was observed for all but one item in Table 3, manganese was the only chemical whose measured concentration showed a statistically significant variation with treatment.

Except for *Salix scouleriana* and *Quercus palustris*, manganese concentration tended to increase with time for the control, pH 4.0, and pH 3.5 treatments. Large increases, up to a factor of nine, were observed for *Fraxinus latifolia*, *Populus trichocarpa*, and *Ulmus americana*. Increases were somewhat smaller at pH 3.5 than at pH 4.0 or in the control.

Manganese concentrations also increased during the first 90 days at pH 3.0. However, from 90 to 300 days, concentration decreased for at least five of the species for which concentration increased under the other treatments. After 408 days, concentrations were between 7 and 54% lower at pH 3.0 than for any other treatment. Final concentrations at pH 3.0 were lower than control concentrations for all measured species.

Results given to this point have been for dry weight or for elemental concentration. As an example of effects on total elemental content (i.e., weight times concentration), Table 4 gives total amount of Kjeldahl nitrogen per leaf pack for the control and pH 3.5 treatments, expressed as ratios to initial values. Table 4 also compares the ratio of final N contents for these two treatments to the ratio of weights predicted by entering the k values of Table 1 into the regression equation of weight vs. time.

Table 4 demonstrates that differences between treatments in total N content were dominated by differences in decay rates. For example, after 408 days (1.12 years), each leaf pack of *Acer macrophyllum* had 44% as much N at pH 3.5 as at the control pH, and weighed 48% as much (based on a regression equation). This is consistent with the observation that, in general, k values (Table 1) but not concentrations (Table 3) were affected by pH. Thus, k values in Table 1 can be used to estimate relative differences in weight loss or in total elemental content associated with sulfuric acid rain treatment.

Variations in total-N dynamics with time are indicated by Table 4. During the first 90 days, total N increased (indicated by entries greater than 1 in Table 4) for almost all species; this occurred for all treatments. N content then tended to decrease, with values at 300 days generally lower than at 90 days; rain at pH 3.5 tended to enhance this decrease. The most striking effect of acid rain on N dynamics is evident for *Ulmus americana* and *Lirodendron tulipifera* after 408 days; rather than being conserved (*Ulmus americana*) or increased (*Liriodendron tulipifera*), N was lost from the leaf packs under the pH 3.5 acid rain treatments.

Discussion

Simulated sulfuric acid rain clearly affected the decomposition rates of leaves of several hardwood species. However, the mechanism and significance of these changes are unclear.

The differences in decomposition rates associated

TABLE 3. Elemental concentrations at end of study (408 days) expressed as ratios to corresponding initial values (Table 2); p_1 and p_2 are significance levels (probabilities of type I error) based on F tests for time and treatment effects. Numbers in parentheses are values after 300 days, given if final values were unavailable

Species	C	N	S	K	Ca	Mg	P	Fe	Sr	Mn	
										pH 5.6	pH 3.0
Acer macrophyllum	0.8	1.1	0.8	0.4	—	(2.0)	0.8	30.8	0.9	—	0.6
Populus trichocarpa	1.0	1.4	1.0	0.5	1.0	0.8	1.3	8.8	0.9	2.7	1.8
Quercus garryana	0.9	(1.2)	(1.2)	0.6	0.6	—	1.1	2.0	0.8	1.4	0.8
Fraxinus latifolia	0.9	(1.5)	1.3	0.5	0.3	—	1.2	19.3	0.7	6.1	5.3
Ulmus americana	1.0	1.7	2.2	0.6	0.9	0.6	1.2	8.0	1.0	3.8	2.6
Liriodendron tulipifera	1.0	1.9	1.2	0.3	0.4	—	2.5	(30.5)	0.7	—	0.6
Salix scouleriana	1.1	1.6	1.0	0.2	1.3	0.5	1.1	13.0	1.4	0.7	0.6
Liquidambar styraciflua	1.0	—	1.2	0.2	0.9	—	1.2	—	1.5	—	0.4
Platanus acerifolia	1.0	1.3	0.5	0.4	1.0	0.6	1.1	8.4	0.9	1.9	1.3
Quercus palustris	1.0	2.1	(1.7)	0.4	4.1	0.8	1.7	2.5	3.5	1.0	0.5
p_1 (time)	0.023	0.002	<0.001	<0.001	0.066	0.178	0.001	<0.001	0.013	<0.001	
p_2 (treatment)	0.975	0.999	1.000	0.521	0.968	0.415	0.492	0.115	0.984	0.001	

with sulfuric acid rain did not depend in an obvious way on the initial elemental contents of the leaves. Abrahamsen *et al.* (1980) also found that the effects of acid rain on decomposition rates could not be explained by measured chemical contents. However, the rankings of control decomposition constants k_c (Table 2) followed established patterns with respect to initial chemical content (see Jensen 1974; Williams and Gray 1974). Specifically, high k_c values were associated with narrow C:N ratios and high base content. Thus, if a similar relation existed between acid rain effects and initial concentrations, we probably would have observed it. However, a complex relationship involving several inorganic and organic chemicals is possible; such relationships are thought to be important to decomposition processes (see Williams and Gray 1974).

In addition, there was no obvious connection between k_c value and sulfuric acid rain effect. In particular, species with low k_c values were not affected relatively more than species with high k_c values (Table 2). This observation, along with the lack of a relationship between sulfuric acid rain effect and initial elemental content, suggests that sulfuric acid rain did not enhance decomposition by correcting an elemental imbalance. Specifically, the fact that neither k_c nor $k_{3.5}$:k_c depended on sulfur concentration or on S:N suggests that simulated sulfuric acid rain did not stimulate litter decomposition by supplying sulfur; however, the sulfur in the rain was undoubtedly more readily available than the sulfur originally in the leaves. Lee and Weber (1982) showed that sulfate concentrations in simulated sulfuric acid rain were greater after the rain had percolated through sugar maple (*Acer saccharum* Marsh.) or red alder (*Alnus rubra*) litter. Thus the relative amount of sulfur in a soluble, readily available form could be affected by sulfuric acid rain even in the absence of an effect on total sulfur content. Future studies should: (*i*) determine the effect of acid rain on the form of sulfur in decomposing leaf litter; (*ii*) differentiate between sulfur in foliage and in biota; and (*iii*) determine the source of sulfur (rain or foliage) utilized by biota.

The response to rain at pH 3.5 might reflect a pH optimum for the decomposing biota, especially fungi. This could be caused directly by effects on the organisms, indirectly by conditioning of the leaves, or by a balance between direct and indirect effects. However, within leaf litter, the pH is probably at a value higher than 3.5, since leaf litter can significantly raise the pH of acid rain (Lee and Weber 1982; Roberts *et al.* 1980; Fairfax and Lepp 1976). Thus, the chemical environment (including acidity) was different from that in laboratory studies on the effects of acidity on decomposer organisms at the same nominal pH; results from one type of study are not readily transferable to the other type.

TABLE 4. Total amount of Kjeldahl nitrogen at each time as ratio to initial amount

Species	Control			pH 3.5			Ratios of final (408 day) values for two treatments	
	90 days	300 days	408 days	90 days	300 days	408 days	Total N	Weights*
Acer macrophyllum	1.03	0.72	0.09	1.00	0.22	0.04	0.44	0.48
Populus trichocarpa	1.17	0.96	0.30	1.16	0.62	1.19	0.63	0.49
Quercus garryana	0.99	0.46	—	1.03	0.68	—	(1.48)†	(0.91)†
Fraxinus latifolia	0.95	0.71	—	1.17	0.17	—	(0.24)	(0.45)
Ulmus americana	1.03	1.02	1.00	1.12	0.52	0.33	0.33	0.38
Liriodendron tulipifera	1.37	1.15	1.28	1.37	0.81	0.14	0.11	0.22
Salix scouleriana	1.15	1.15	1.22	1.29	0.95	0.98	0.80	0.72
Platanus acerifolia	1.00	1.08	1.15	0.99	1.04	1.00	0.87	0.91
Quercus palustris	1.11	1.51	2.38	1.08	0.68	2.13	0.89	0.68

*Ratio of weights predicted from k values for two treatments from Table 1.
†Numbers in parentheses refer to ratios at 300 days, given only when ratios for 408 days were not available.

A field study at a location outside the region of highly acidic rain found that manganese concentrations increased during leaf decomposition (Lousier and Parkinson 1978). However, field studies at sites subject to ambient acid rain found both increases (Lawrey 1978) and decreases (Gosz *et al.* 1973) in manganese concentrations. Our results suggest a pH threshold for greatly increased manganese mobility. The increased leaching of manganese observed in this study at pH 3.0 raises the possibility that the decrease in k from pH 3.5 to pH 3.0 might have been associated with mobilization of trace metals, possibly to toxic levels. Similar processes are implicated in the adverse effects associated with acidification of soils (Brady 1974).

The increases noted in the total amount of Kjeldahl nitrogen in decomposing leaves are interesting and parallel findings in other studies (Bocock 1964; Gosz *et al.* 1973; Howard and Howard 1974; Lousier and Parkinson 1978; Anderson 1973). Possible sources of nitrogen, as suggested by various authors, were summarized by Lousier and Parkinson (1978). These included atmospheric nitrogen, precipitation and throughfall, dryfall of dust and fresh organic matter (insect frass, green litter), and inorganic nitrogen in the soil and litter. In our experiment, nitrogen accumulation in leaf packs during the first 90 days was considerably greater than the amount of nitrogen supplied by the simulated rain. The roof over the experimental stations was open on the ends and sides, so that deposition of dust was possible. However, rainfall occurs almost daily in western Oregon during the winter, resulting in continuously wet soil and very low concentrations of atmospheric dust. This suggests that dryfall was not an important factor. Similarly, a significant influx of fresh organic matter during these winter months seems unlikely. The most likely sources of nitrogen thus seem to be fixation of atmospheric nitrogen or transformation and translocation of nitrogen originally within each flat. The former could be important only if the litter increased the pH of acid rain to a value above 5.0 (Alexander 1980).

In summary, simulated sulfuric acid rain stimulated the loss of litter, nutrients, and trace metals from the soil surface. These changes were primarily due to alteration of the rates at which litter disappeared from the soil surface, rather than to changes in elemental content of the remaining pieces. By supplying nitrogen, nitric acid rain might further increase decomposition rates (Forbes 1974). Since this is just the first step in organic matter processing, it is not possible to predict the net result on available nutrient pools. However, unless the subsequent steps are seriously depressed by acid rain, these pools should increase, at least for a short time.

The results presented in this paper were obtained by applying simulated sulfuric acid rain to leaf litter under experimental conditions. The effects of ambient acid rain on decomposition processes occurring under natural conditions might not follow the same patterns. If responses are similar in forest settings, then acid rain potentially can cause substantial changes in the rates of loss from the litter layer. The implications of changes in the dynamics of this storage component of the ecosystem can be evaluated only by considering litter decomposition in the context of ecosystem dynamics. For example, increased availability of nutrients could lead to increased production of foliage. The resulting increase in litter would tend to offset depletion of the litter layer. Alternately, release of nutrients prior to the peak growth period could ultimately lead to decreases in nutrient pools through increased opportunities for

leaching. Thus, net long-term effects on forest productivity depend on complex chemical and biological relations within the soil, and on the relative seasonal timing and magnitudes of nutrient supply, leaching, and uptake by plants.

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